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The emergence of magnetic fields with hypersonic velocities as a source of flare activity in the solar chromosphere

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In the previous article, it was shown that Parker's instability of a thin magnetic tube located within the convective zone may be responsible for the generation of an impulsive CME.

In the present paper, it is shown that the heat conductivity along the tube can alter the energy balance of the apex of the emerging magnetic arc considerably, resulting in a faster acceleration of the emerging tube, and a higher speed achieved, and a bigger height of the rise compared to the simulations without heat conductivity. Heat flows are the most powerful when the magnetic tube is moving inside the solar chromosphere.

Keywords: Coronal mass ejections: Magnetic tube: Solar convective zone: Solar activity

1 Introduction

It is well acknowledged that solar flares, eruptive protuberances, coronal mass ejections (CMEs (Alekseenko et al. 2012a, Temmer et al. 2010, Somov & Titov 1985)) are the results of a powerful destabilization of a coronal magnetic field by a new magnetic flux emerging from the subphotospheric regions (MacQueen & Fisher 1983). The modern observational instruments allow us to resolve that the magnetic structures in the solar atmosphere are constructed from many well-organized magnetic tubes located in an almost field-free plasma of the Sun (Knoelker & Schuessler 1988).

The key element of the study is a thin magnetic tube located in an almost field-free plasma. The physical mechanism of generation of the thin magnetic tubes is noted in the interplay between emerging large-scale magnetic structures and convective plasma flows in the convective zone (Parker 1979a). External layers of the large-scale structures are split on isolated thin magnetic fibrils by the turbulent convective flows (Moreno-Insertis et al. 1992); the fibrils then emerge into the solar atmosphere. The thin magnetic tube is subject to few instabilities with the most important being Parker's instability of the slow mode of magnetic field oscillations. For the case of the

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the upper layers of the convective zone of the Sun and the short wavelengths (wave number $m \geq 20$) the instability is investigated in Alekseenko et al. (2012b)).

Results of numerical simulations of the emergence of magnetic flux into solar corona (including the nonlinear stage and saturation of Parker's instability (Romanov & Romanov 2001)) without heat conductivity taken into account are shown in Romanov et al. (2015).

Unlike the convective zone, the heat flow becomes important in the solar atmosphere and the transition region. This paper addresses the contribution of thermal heat conductivity into the dynamic of the rise of the magnetic tube from the convective zone to the solar atmosphere simular to Romanov et al. (2015).

2 Mathematical formulation of the problem

To validate the applicability of the thin magnetic tube approximation, typical parameters of a plasma inside and outside the tube are used for the entire solar convective zone (Christensen-Dalsgaard et al. 1996).

Within the convective zone, the microscopic parameters of plasma are significantly smaller than the scales of the moving magnetic tube, so the ideal magnetohydrodynamical approximation is valid to describe the problem.

In turn, the thin tube approximation holds if these conditions are satisfied:

$$\tau \gg \frac{a}{\min(c_s, V_a)} \tag{1}$$

$$a \gg \frac{P}{\rho \cdot g} \tag{2}$$

Here τ is a characteristical time scale of the problem, $V_A = \sqrt{H^2/4\pi\rho_i}$ is an Alfvén speed, $c_s = \sqrt{\gamma p_i/\rho_i}$ is a speed of sound inside the tube. Equation 2 means that the radius of the tube is small compared to the local pressure scale-height of an external media, while eq. 1 ensures the pressure is in equilibrium across the tube. Under these conditions, the tube does not perturb the external media significantly when the tube moves in the convective zone.

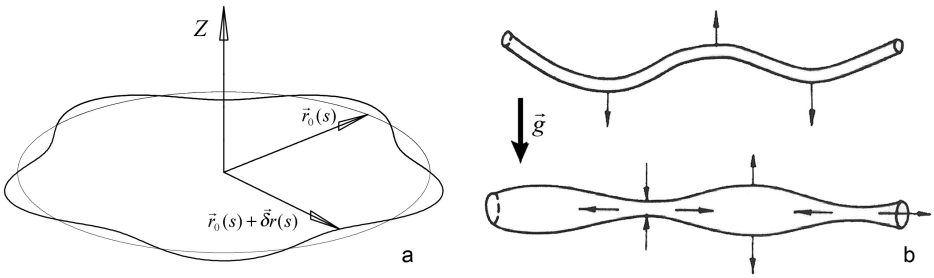


Figure 1 The shape of the tube for a perturbation with wavenumber $m = 5$ (a); the structure of plasma flow inside the tube for Alfvén and slow waves (b).

The full system of equations is written using Lagrangian mass variables (Romanov & Romanov 2003):

$$\begin{cases} \dfrac{\partial \vec{r}}{\partial t} = \vec{v} \\ \rho_i \dfrac{\partial \vec{v}}{\partial t} = \vec{f} \\ \vec{f} = \dfrac{H \cdot \sigma \cdot \rho_i}{4 \cdot \pi} \cdot \dfrac{\partial (H \cdot \vec{\ell})}{\partial s} + (\rho_i - \rho_e) \cdot \vec{g} \\ \dfrac{\rho^\gamma}{\gamma - 1} \cdot \dfrac{\mathrm{d}}{\mathrm{d}t} \left(\dfrac{p}{\rho^\gamma} \right) = -\mathrm{div} \vec{W} \\ \vec{W} = -k(\rho,\ T) \cdot \vec{\nabla} T \\ p_i + \dfrac{H^2}{8 \cdot \pi} = p_e \\ p_i = \dfrac{R}{\mu} \cdot \rho_i \cdot T_i \\ H \cdot \sigma = H_0 \cdot \sigma_0 = const \\ \vec{\ell} = \rho \cdot \sigma \cdot \dfrac{\partial \vec{r}}{\partial s},\ |\vec{\ell}| = 1 \\ \varepsilon = \dfrac{1}{\gamma - 1} \cdot \dfrac{p}{\rho} \end{cases} \tag{3}$$

Here $\vec{f}$ stands for a force per unit volume of the plasma of the tube. The system consists of three equations of motion, the magnetic flux conservation law, the transversal pressure balance equation and the continuity equation. To complete the system, one requires $p_e(\vec{r})$, $\rho_e(\vec{r})$, $g(\vec{r})$ which are taken from the model of the internal structure of the Sun (Christensen-Dalsgaard et al. 1996). The equation of energy takes into account the heat conductivity along the tube.

The first step is to address the linear stability of the magnetic flux in the convective zone of the Sun. In the initial unperturbed state, the tube is assumed to be in mechanical equilibrium and rest in the equatorial plane of the Sun (Fig. **??**a) in a form of a ring with radius r_0. Perturbations are standing waves defined by the wavenumber m (a number of wave periods along the whole tube).

The linearized system of equations (3) has two solutions corresponding to the fast (Alfven) and the slow magnetosonic wave running along the tube (Fig. **??**b) (Alekseenko et al. 2012a). The gravity introduces instability with the slow waves first to become unstable. This is the famous Parker's instability: regions with higher density exponentially sink while ones with decreased density emerge if the magnetic field tension fails to counterbalance the buoyancy force (Parker 1979b).

3 Results of numerical simulations

The buoyancy force makes the slow wave the most unstable. During the initial stage of Parker's instability development (Parker 1979b) the tube forms a wide arc with the foot sinking deeper into the convective zone (Fig. **??**).

The gravitation supports a plasma downflow in the legs of the arc, while the apex of the arc nonlinearly gains speed, loses matter, and emerges through the photosphere

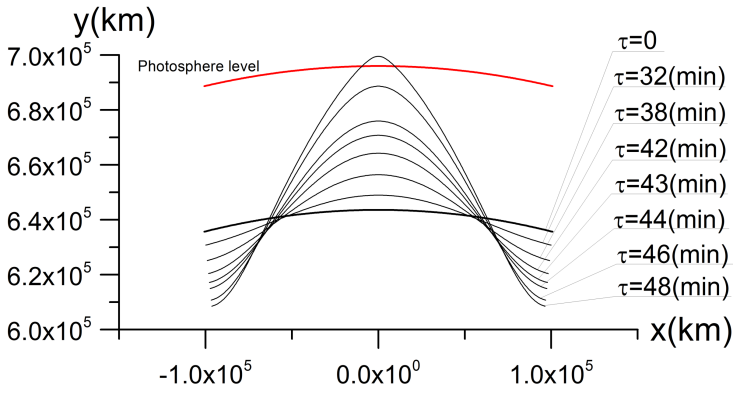


Figure 2 The initial stage of Parker's instability development.

into the atmosphere of the Sun. In the atmosphere, the heat conductivity additionally accelerates the process.

The linear analysis shows that either the increase of magnetic field strength or the decreasing of wavelength (increasing of wave number m) stabilizes the tube against Parker's instability thanks to $(\vec{H},\vec{\nabla})\vec{H}/4\pi$ term in eq. (3).

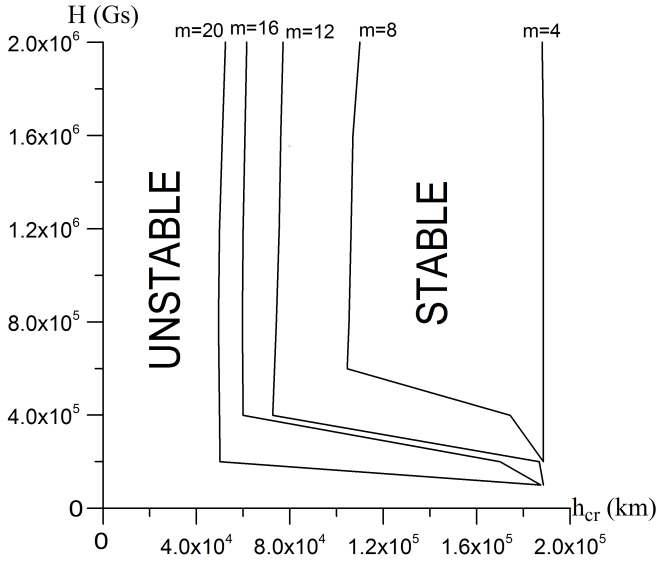


Figure 3 Parker's instability regions in a parameter space of the wave number m, the magnetic field strength H, and the depth under the surface of the Sun.

The critical magnetic field strength required to stabilize Parker's instability as a function of a wave number m and the depth in the convective zone is presented on Fig. **??**. It is found using linear stability analysis (Romanov & Romanov 2003) using the model of inner solar structure (Christensen-Dalsgaard et al. 1996). Calculations are performed for a wide range of the magnetic field strength: $0 \leq H_{cr} \leq 2 \cdot 10^6$ Gs.

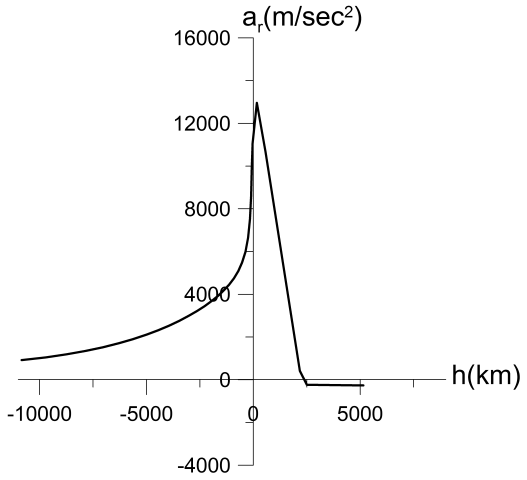


Figure 4 Acceleration of apex of the magnetic arc as a function of height.

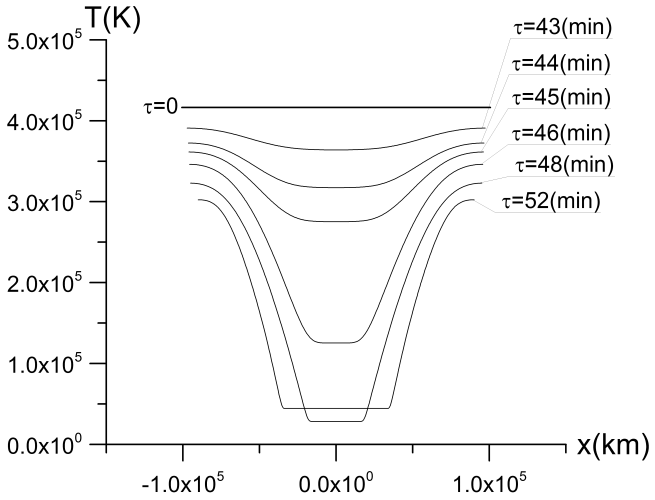


Figure 5 The temperature of plasma inside the tube as a function of time.

This distribution is a starting ground in a modeling of the development of Parker's instability.

Parker's instability development is studied in a short wavelength region of the spectrum ($m \geq 20$, $\lambda \leq 2 \cdot 10^5$ km) to address the case of nonlinear ejection of a magnetic field into the solar corona (Romanov et al. 2015). Wave mode $m = 20$ becomes unstable at 58000 km under the surface of the Sun. The initial strength of the magnetic field $1 \cdot 10^6$ Gs. The temperature of the plasma inside the tube is $3.637 \cdot 10^5$ K, and outside $4.339 \cdot 10^5$ K. CME formation takes place in two stages.

The initial stage of Parker's instability development is typical. An arched magnetic tube emerges to the surface with an increasing acceleration (Fig. **??**) due to the plasma down-flows (Fig. **??**) along the legs of the arc.

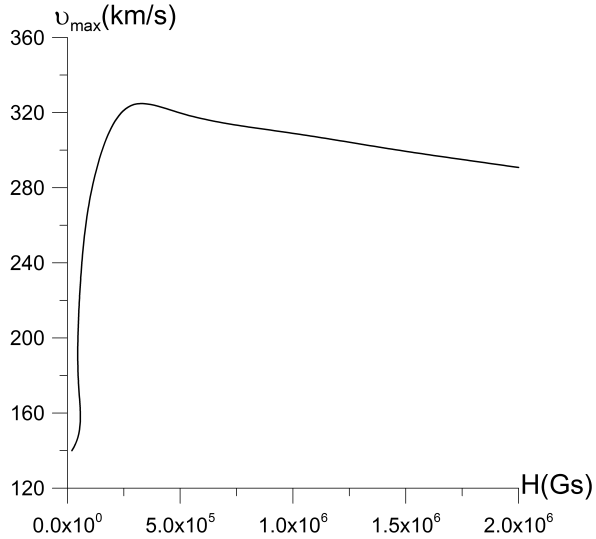


Figure 6 Vertical speed of apex of the magnetic structure as a function of H_{cr}.

Formation of an arc structure is accompanied by a growing temperature gradient along the tube which leads to a nonlinear increase of a heat flux directed from the base to the apex of emerging magnetic structure (Fig. **??**). Assuming the initial transversal size of the magnetic tube about 1 km, the final heat flux may reach $2.8 \cdot 10^{30}$ erg/sec (Fig. **??**).

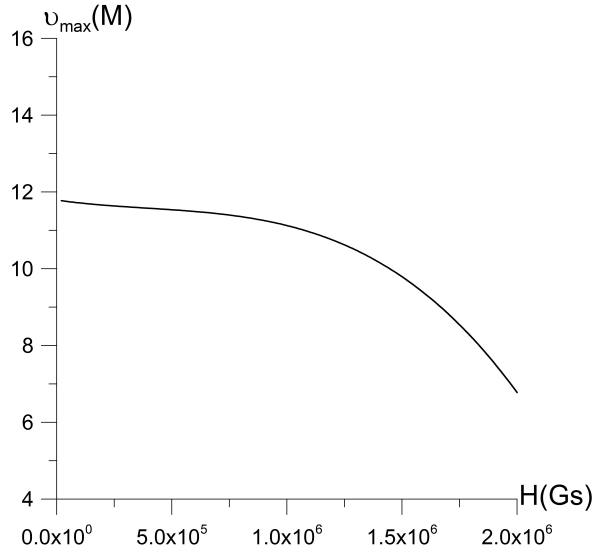


Figure 7 Vertical speed (in Mach numbers) of apex of the magnetic structure as a function of H_{cr}.

The second stage of the CME formation begins when the apex enters the upper chromosphere of the Sun. At heights of about 2000 km, the temperature grows

nonlinearly due to an anomalous heating of the solar atmosphere (Prist 1982). The difference of the temperature inside and outside of the tube in the solar atmosphere may reach 20000 K due to the incoming upward heat flux along the tube (Fig. **??**).

It results in a high acceleration of the tube preserved even in the solar chromosphere (Fig. **??**). As a result, the tip of the magnetic structure acquires speed equal to 320 km/sec (Fig. **??**) which is an order of magnitude faster than the local speed of sound.

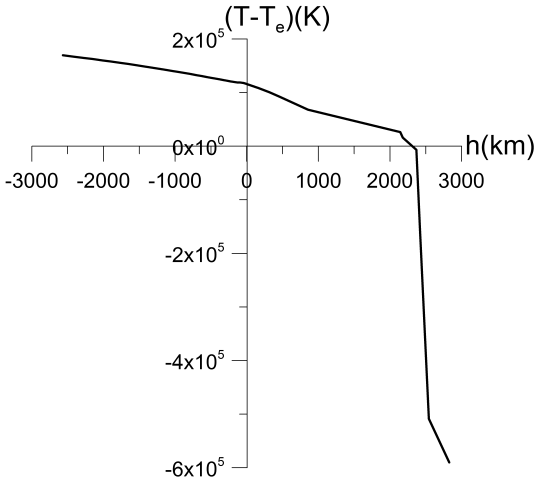


Figure 8 The difference of temperature between internal and external plasma of the tube as a function of height.

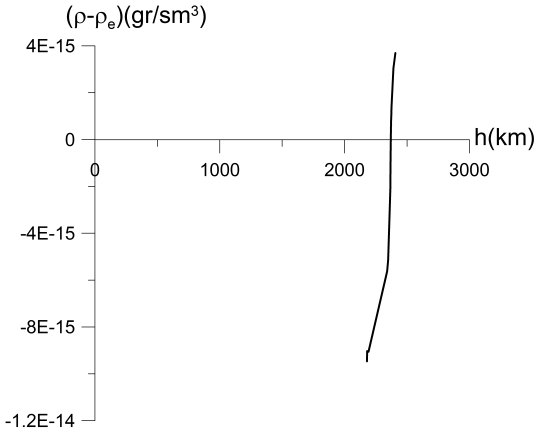


Figure 9 The difference in plasma density inside and outside of apex of emerging magnetic arc as a function of height.

Due to the anomalous heating of the solar atmosphere, the temperature of an external plasma increases up to 10^6 K in lower corona. The temperature difference changes sign at the height equal to 2300 km above the photosphere (Fig. **??**). The difference in the density of plasma inside and outside of the tube behaves accordingly (Fig. **??**).

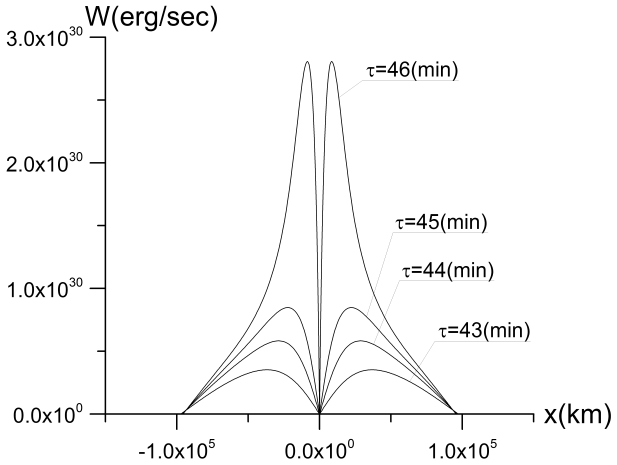


Figure 10 Distribution of full heat flux along the tube for several moments in time.

When the density of the plasma inside the tube exceeds the density of external media due to the difference in the temperature, the buoyancy force changes sign and the tube starts to decelerate (Fig. **??**). It is important that heat flux reduces the magnitude of the deceleration, so the tube may emerge to a final height of the order of $160 \cdot 10^3$ km where it stops (Fig. **??**).

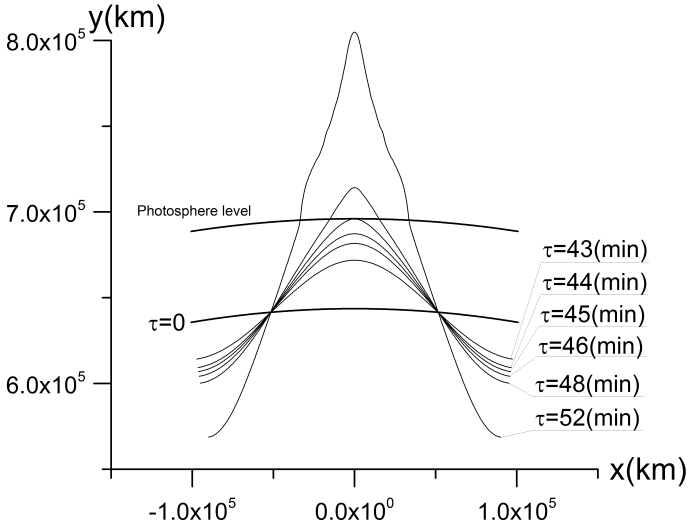


Figure 11 Time history of the formation of CME.

The magnetic tube in the chromosphere can be observed as a cavity (Eselevich & Eselevich 2001). The present case is similar to Romanov et al. (2015): no original magnetic field structures located on the trajectory of the rising tube except for the quasi-stationary solar wind, the tube emerges to become a foundation of the impulsive CME in the clear atmosphere (Eselevich & Eselevich 2001). Now the maximum speed

of rising is about 300 km/sec and holds in the entire upper chromosphere (Fig. **??**). The speed practically does not depend on the initial field strength. As a result, the magnetic tube crosses the solar chromosphere with a hypersonic velocity.

4 Conclusion

To analyze the different types of CMEs (Eselevich & Eselevich 2001), it is crucial to separate the two stages of the emergence into the solar atmosphere.

The first (explosive) stage of accelerated emergence up to the upper solar chromosphere always takes place. At the nonlinear stage of Parker's instability development, the speed of the tube may be of the order of 300 km/sec. It is the significant result considering the analysis of the physics of solar flares (Severny 1988) and the CME in a pure solar atmosphere (Eselevich & Eselevich 2001).

The physics of the second stage of the emergence into the solar corona depends on the radius of the tube. The thick magnetic tube is opaque with respect to radiation heating by the surrounding chromospheric plasma. An internal plasma of the tube is heated by the upward heat flux along the tube from the hot base rooted in the convective zone. It introduces a new height with a temperature of the external media close to the temperature at the base of the tube. Taking into account the nonstationary rapid acceleration of the rising, the tube emerges above this level. After a deceleration, the tube falls down in the form of coronal condensation. Solar prominences are formed this way (Severny 1988). Figure **??** demonstrates that the depth of Parker's instability development grows as wavenumber m decreases. The temperature of plasma in the convective zone grows nonlinearly with depth as well (Christensen-Dalsgaard et al. 1996). That means that the power of the heating also grows due to the higher temperature of the thermal energy source. It opens an interesting prospect in studying the physics of a giant prominence in the solar atmosphere (Severny 1988, Prist 1982).

The explosive rise of the magnetic field from the subphotospheric layers to the solar chromosphere is of fundamental importance for analyzing the flare processes in the active regions of the Sun. During the nonlinear phase of the instability development, acceleration is performed by a magnetic field with velocities of the order of 300 km/sec ($M \simeq 10 \div 12$) (Fig. **??**). The maximum increase in acceleration does not depend on the initial magnetic force of the tube and is reached in the upper layers of the solar chromosphere.

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